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2nd International Through-life Engineering Services Conference

Information systems challenges for through-life engineering

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Information technologies hold great promise in achieving reduction in through-life support costs for long-lived complex artefacts such as aircraft and ships, and may allow very much improved assessment of asset condition, but in order for these to be achieved a number of technical and socio-technical challenges have to be overcome. Based on a perspective gained in the EPSRC Knowledge and Information Management Through-Life Grand Challenge project this paper gives an overview of these challenges, of recent research achievement and of areas where further research is needed. In particular, it notes that it is important to identify what information needs to be captured through the life of the artefact and how the information may be organised and sustained over long timescales. Important standards are reviewed, as are emerging developments such as classification systems and ontologies for organisation and the use of lightweight representations and annotation. Finally, socio-technical challenges including data accuracy and quality issues, security and privacy and the latency in multi-faceted information systems are reviewed.

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Keywords: Through-life engineering, information systems, knowledge management, information standards;**1. Introduction**

The demanding life cycles of today's complex, long-lived artefacts such as aircraft, ships, buildings and power generation equipment mean that it is more important than ever for the operator and user of the artefact to have good information about its operational status and condition and for the designer to learn from experience of the artefact in use. This is especially true when many people from different organisations, often widely geographically distributed, may be involved throughout the life cycle. With good information about the state of the artefact the cost of maintenance may be controlled, life extension may be considered and product-service arrangements may be entered into with acceptable risk.

In this context information about the asset and its state, the environment to which it is subjected, the decisions made at design time, the configuration actually achieved during manufacture and the operations carried out in modification,

service and repair are all very important. Information technologies offer very significant potential in this regard, and indeed are proposed as a key means of achieving future productivity increases, but before this potential can be realised a number of challenges have to be overcome. The aim of this paper is to give an overview of these challenges and to suggest areas where research is needed.

Much of what is presented here arose from the EPSRC/ESRC-funded Grand Challenge project in Knowledge and Information Management Through Life (the ‘KIM project’ [1]) in which the authors participated. In particular, results are presented from two work packages which explored product information representation and management for the whole life cycle (Work Package 1, WP1) and learning through the product-service life cycle (Work Package 2, WP2). From these work packages a number of challenges were identified in identifying what information to capture through the life of

an artefact and the information technology and socio-technical issues in its organisation and management.

2. What do we need to capture?

Our current digital world allows us to capture data all the time: from people during all manner of work, using many different sensors, from all sorts of physical devices, around the world, in the air and at sea. But what should we capture and retain? We are constrained now not by the ability to capture but by our ability to retain, organise and interpret the information (and to some extent by our ability not to be overwhelmed by the quantity of data that we can capture). As part of KIM WP1, Heisig et al. did a survey in which they asked respondents to reflect upon their engineering tasks and to describe the information and knowledge that (1) they would like to retrieve from previous products/services, and (2) that they think should be captured to assist future engineering tasks [2]. Respondents were asked to consider knowledge and information needs throughout the whole product life cycle from initial concepts via manufacturing and deployment to the disposal of the product.

Heisig et al. confirmed what has been shown in many studies that a great diversity of data is produced relating to any engineering artefact at all stages of the life cycle. This data is in many different formats, often proprietary and often including very complex data types. The first key challenge in engineering is the sheer number of different aspects to be covered, but perhaps of paramount importance is the need to retain information relating to the physical configuration of the artefact, as designed, as built and modified to any condition through life. For designers the key importance was being able to revisit at any stage the rationale behind decisions made during the design stage.

More specifically, the results presented in [2] list sixty-nine different categories of knowledge and information that emerged from responses of design engineers and managers, service engineers and software engineers from aerospace, engineering and consulting companies in the United Kingdom. The categories span the whole product life cycle covering for example obvious things such as ‘design requirements’ (and any changes over life), the full geometry and arrangement of the designed artefact, information about how it was manufactured, the performance of the artefact compared with how it was intended to perform, full details of the configuration, including any changes or modifications made compared with as-built and as-developed, planned and achieved reliability data for end-user support, maintenance plans, records and history, as well as information on aspects like reparability and maintainability. The respondents also yielded in their answers some requirements for support systems, which could be summarised as follows: one single place from which to retrieve knowledge and information; visual aids like maps to support navigation from the ‘big picture’ as high-level overview to component-specific details; multi-format importing; and applications supporting the traceability of information and the evolution or history of the design.

2.1. Capturing the inter-dependency of engineering data

Through-life engineering data is a challenge because of its diversity in terms of the number of different aspects of the artefact and its design, development and operation that are captured through the lifecycle. It is also a challenge because in order to understand and exploit the data the context in which it has been generated and the relationships among the data, the artefact and the stages of the life cycle need to be known. For example sensor data captured on some aspects of artefact condition or a maintenance record is in itself of little merit: it needs to be linked to the artefact and the context/environment in which it has been generated to be valuable. In a study done in the context of research data management (although it is proposed here that many of the same issues apply for engineering data), Ball et al. [3] note that for other researchers to re-use and re-purpose data it must be able to be found and it must be in a fit state. This has implications for how the data are managed. Especially to remain explicable and meaningful the data must be fully documented and contextualized. In support of this they propose a formal data management terminology, noting the following activities:

- Data use: using data for the current purpose/activity.
- Data re-use: using data for a purpose/activity other than that for which it was intended.
- Data purposing: making data available and fit for the current activity.
- Data re-purposing: making existing data available and fit for a future known activity.

In order to support data re-use, Ball et al. propose that in addition to the primary data records the information collection should also include data records describing the context in which data have been generated or collected: for example records containing data that describe any methodology applied, explanatory narratives, dictionaries, ontologies, standards documents or environmental data. They also propose that associative data records should be created to make explicit the associations between other data records or data. These associative data records classify research data into types and assign other useful attributes allowing development of a formal means of modelling known as Research Activity Information Development (RAID) diagrams, using UML as a representational language (combining elements from the UML static structure and UML activity diagrams), to provide a visual mapping of the data records associated with a research activity (at any chosen level of activity granularity), showing the chief attributes of each data record and the relationship between it and other records in the data case. The RAID modelling approach becomes a means of managing data during their development so as to support their later interpretation and understanding for re-use and re-purposing. A similar capability is needed in through life service data.

3. Information technology challenges

As well as the high level data management issues that allow the context and use of engineering data to be understood, many computing issues have to be addressed if the data are to be a useful resource over the long life of many engineering artefacts. Ball et al. [4] note that artefact life cycles in engineering in the order of decades can lead to problems in two respects. Firstly, information generated over the artefact life cycle needs to be able to be accessed over potentially many generations of computer hardware and software. Secondly, many changes, to both the artefact and to its environment, occur over the life cycle, and strategies are needed for updating, reporting and merging these changes at different semantic levels. In this section we consider the three challenges of sustaining data over long timescales, ensuring that data are compatible and interoperable, and organising data such that it can be discovered and exploited.

3.1. How do we ensure that the data are compatible and interoperable?

One of the major problems facing long-term users of engineering data is a lack of compatibility between software systems, specifically between competing systems and between different generations of the same system. A good deal of difficulty comes from the incorporation of proprietary features in software tools, and from differences in the conceptual design of such tools. In consequence, data created using a particular piece of software is in danger of becoming inaccessible to its creators once that piece of software is retired or replaced. For many years these issues have been addressed by data exchange standards including the Initial Graphics Exchange Specification (IGES), and the so called STEP (STandard for the Exchange of Product Model Data) standard, ISO 10303, for Product Data Representation and Exchange [5]. Recent work on data exchange has been built around STEP, with the standard being extended to electrical and electronics design information, engineering analysis data, the information requirements of systems engineering, process planning for manufacture and life cycle support, the latter through AP239 (Product Life Cycle Support [PLCS]) [6]. AP239, which covers four key areas – support engineering, resource management, configuration management, and maintenance and feedback – aims to support the exchange of product information throughout the product lifecycle, extending the capabilities of other parts of the STEP standard to cover the entire lifecycle and product support domain based on a single integrated information model. AP239 is independent of specific processes so that it can be flexibly tailored according to different industry requirements. The implementation of AP239, however, is still a challenge [7]. Other developments also involve STEP technologies being exploited in other domains (e.g., in the definition of cutting tools and optics and optical instruments), and complementary technologies are being incorporated into STEP – for example in the use of the eXtensible Markup Language (XML) to describe STEP schema [8]. XML is also the basis for the Product Data Exchange (PDX) series of standards developed

for the electronics manufacturing supply chain [9]. Both XML and the Unified Modelling Language (UML) will have important implications for product representation and exchange in the future. However, in spite of this extensive development of STEP, the practical application of the standard is patchy.

There are various reasons for the patchy application of STEP. The standard covers the whole product lifecycle so that the potential volume and range of software objects (as noted above) is extensive. Furthermore, members in the extended enterprise lack STEP knowledge, which may slow down the implementation and result in higher training costs [10]. Ball et al. note also that the use of EXPRESS as the modelling language to describe the data and information models in STEP means that there is no straightforward way to express constraints other than those envisaged when the standard was published, or to make explicit constraints that are identified and captured during project planning and the early design stage [4]. In addition, while the models used in computer-aided engineering systems are well established, many systems implement a hybrid-modelling strategy combining the best features of the various approaches and the proprietary nature of these implementations limits interoperability.

An alternative to full STEP implementation is to work with simpler, lightweight formats which may translate easily to other formats. Although such formats (e.g. Universal 3D [11], X3D [12], 3D-XML [13], JT Format [14]) do not capture the full complexity of the data possible in heavyweight formats they can be used more readily at different stages in the product life cycle (e.g. in manufacture or service) without the need for expensive proprietary software. They are also often easier to comprehend and they (generally) open nature makes curation more straightforward.

A second aspect of the approach proposed in the KIM project was to combine lightweight formats with markup languages. Markup languages are very important in the World-Wide Web, are subject to very accessible and robust standards and are human readable. The project described how they could be used to allow life cycle information to be associated with part geometry and other product data through annotation – for example to note the presence of damage or to record service operations. Furthermore, by using stand-off markup (annotation stored separately from the geometry model but mapped to it) and ensuring that the lightweight models are mappable to the original high fidelity data then different layers of information can be associated with the same underlying model and this can be used as a basis for knowledge discovery, for control of intellectual property, etc. [15]. Figure 1 shows how stand-off markup can be combined with different lightweight representations at different stages in the product life cycle. More recent work has involved the representation of the annotation in ontologies, which again can be rendered in open standards. Li [16] suggests that this approach may form the basis of modern lightweight easily interpretable standards for coordination of product life cycle data and the re-use of that data through intelligent processing of the annotation. Brunsmann and Wilkes [17] propose using annotations encoded using a standard ontology to ‘fill in’

engineering knowledge that is missing or incompletely expressed in preservation surrogates of product data. By also mapping file format semantics to the standard ontology, and migrating these annotations and mappings as the ontology evolves, the engineering significance of the product data can be sustained.

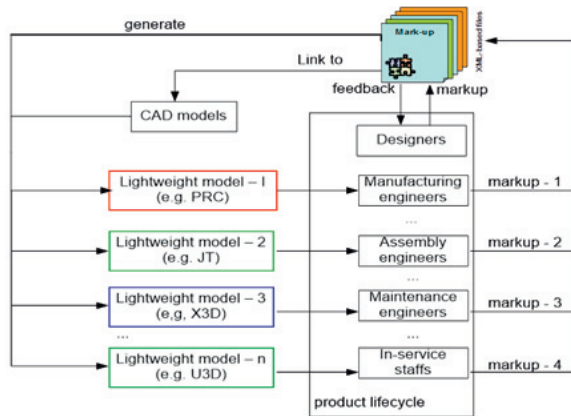


Fig. 1. Lightweight models and markup through the product life cycle

3.2. How do we sustain the information over long timescales?

Standards and lightweight representations make it easier to achieve interoperable data but they do not ensure that data are accessible over multiple revisions of hardware and they do not in themselves provide a framework for coordinating over software revisions. For that we need to set up and manage an appropriate archive, and for guidance in this we turn to the ISO Open Archival Information System standard, ISO 14721:2012. This standard, based on work done originally by NASA and the Consultative Committee for Space Data Systems, defines an information model that conformant archives should support and a set of responsibilities they should fulfil. It does not prescribe how an archive should fulfil its responsibilities, but does provide example mechanisms and a detailed functional model that is useful as a common frame of reference for discussions.

The term ‘Open Archival Information System’ is defined as a repository or archive, ‘consisting of an organization ... of people and systems, that has accepted the responsibility to preserve information and make it available for a Designated Community,’ the latter being ‘an identified group of potential Consumers who should be able to understand a particular set of information.’ [18] In the OAIS Information Model, an Information Object is a piece of knowledge in an exchange format, manifested physically by a Data Object (a bitstream, a string of printed characters, etc.). A person interprets information using knowledge from their Knowledge Base (e.g. the ability to read English or to understand a computing language) combined with Representation Information associated with the Data Object – information about how the object has been represented, encoded and formatted, and tools such as viewer applications. In the case of product model data, examples of Representation Information might include software specifications (or the software itself), standards,

company design rules, and so on. As items of Representation Information are often themselves Information Objects, full understanding of one object may depend on a collection of other objects in what is known as a Representation Network. In order to maintain the usability of archived material, the Designated Community commits to maintaining a certain Knowledge Base among its members, and the OAIS commits to bridging any gaps in understanding left by that Knowledge Base with Representation Information. The work of the KIM project included development of a Registry/Repository of Representation Information for Engineering (RRoRIE) which is a Representation Information registry for engineering specific file formats [19].

The operation of an OAIS is described in terms of Information Packages, which consist of Content Information (the information the archive is entrusted to preserve), Preservation Description Information (information necessary to manage the data, e.g. concerning context and provenance) and Packaging Information (information identifying and binding the components of the Information Package). Descriptive Information is used to facilitate finding the information. Figure 2 shows the three types of Information Package: Submission Information Packages sent from the information originator to the archive, Archival Information Packages actually stored by the archive, and Dissemination Information Packages provided by the archive to a user in response to a request. Many of the requirements for Preservation Description Information match the requirements for descriptive data records described in section 2.1 above.

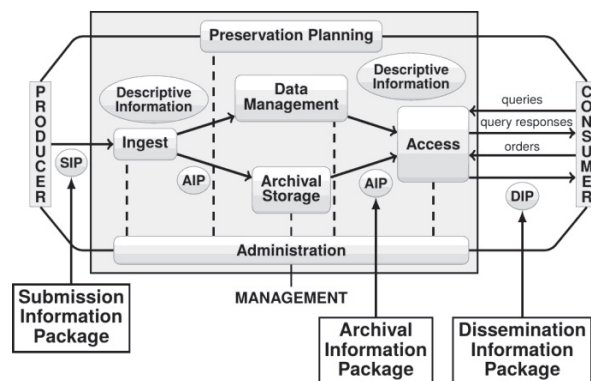


Fig. 2. Information Packages in the OAIS Functional Model

3.3. How do we organise the material?

The information objects that need to be managed for a complex engineering artefact throughout its life may number millions and in order for them to have value to the engineering community they must be organised, firstly so that data can be found as required, and secondly so that new knowledge can be discovered from patterns in the data. While the capabilities of free-text search mean that data can frequently be found by an experienced searcher just by text search, for inexperienced users not familiar with the information or for automated processing some sort of knowledge organization structure is needed. These can take many forms. Traditionally, engineering data has been

organized using the record structures of relational or object databases and engineering structures such as the bill-of-materials, but increasingly alternative approaches such as semantic tagging of data with metadata or the use of classification schemes has been employed. Semantic tagging may be seen as supporting search and automated inference, while classification can assist serendipitous discovery through the browsing of information classifications.

To infer how an artefact is performing in service it is often important that a practitioner can contrast its performance across sufficient operating environments and cases for consistent patterns to emerge. Records from service generally contain information describing the specific conditions under which a fault has occurred, however, where this information is obtained from multiple external sources (as is often the case for in-service queries) the specific terminology and form of the information is subject to significant variance. In such a situation abstracting this information into broader, aggregated and consistent viewpoints may allow emergent patterns to be identified. The abstracted viewpoint may also serve as a browsable organisational scheme, such that past cases may be identified and retrieved and used either directly or indirectly reused when addressing similar issues. Goh et al. present a technique for using such an organisational scheme for service records, in order to identify how emergent issues may ultimately be identified by population and interrogation of the scheme [20].

An organisational scheme provides a means of consistently describing records whose contents share certain features. This allows the contents of each record to be treated identically, regardless of the form and terminology deployed. By arranging such categories within a broader classification scheme, a browsable structure may be generated to facilitate retrieval of past cases. Assigning consistent categorisations also allows common patterns across the assigned categorisations to be identified. Goh et al. note that three distinct forms of classification for knowledge organisation are widely used: the enumerative, the synthetic and the faceted [20]. Enumerative classification involves the recursive partitioning of an information corpus into progressively smaller subsets using some principles of division, whose selection is generally steered by the purpose of the scheme. The best-known application of enumerative classification is probably the computer directory structure. Enumerative classification can be rather arbitrary. By promoting a standard set of principles deployed in a consistent manner, more comprehensible schemes may result. This is basis of synthetic classification, where auxiliary tables have been generated which pre-define the principles of division. Faceted classification takes the idea of consistency to arguably its logical conclusion, identifying that some ‘dimensions’ or facets (not entirely equivalent to principles of division) are so inherent that they may be treated separately. Users are not constrained by the order in which the principles are deployed as per the enumerative classification; instead they may interrogate only those facets of interest. Faceted classification may be seen as having features in common with semantic markup – the facet values are equivalent to metadata. Goh et al. describe how a faceted classification scheme, applied to

aerospace maintenance records, may be used, by treating each concept of interest separately, to allow the user to assemble compound concepts with rapid dynamic feedback concerning the ‘search’ results [20]. In this way the user can arrive quickly at a highly relevant set of results by selecting concepts relevant to a query. In addition, the facets are useful to non-familiar users of the information system. As a result, the system becomes meaningful to others to interrogate, such as designers looking for typical issues raised on a particular component of an aircraft. Finally, the faceted schemes also allow for patterns and trends in the records to be analysed, either by manually browsing the classification tree or automatically using suitable data mining algorithms.

4. Socio-technical Challenges

No matter how good the information technology that is employed, without addressing the socio-technical challenges a satisfactory information system cannot be produced. During the course of the KIM project we came across an organisation in which the staff were so reluctant to comply with rules and strictures that they had been categorised as “institutionally disobedient” and it is clear that in such a case it would not be wise to rely too much on the information systems. The challenges of change management and compliance in the implementation of information systems are well documented, but so is the need to place the needs of users at the heart of system design [21]. In this section we consider some of these ‘people’ issues and challenges in the design and implementation of information systems for through-life support.

4.1. The importance of context.

In [22], Mark Easterby Smith et al. argue that getting the right balance between technical and social approaches to knowledge management systems is a major practical issue, which depends very much on the application context. They suggest that social mechanisms such as communities of practice and informal networks might be most appropriate in the case of service engineers with geographical areas of responsibility maintaining equipment in industrial firms. By contrast, technical knowledge management systems based on information technologies may be more appropriate, at least as the starting point, in the case of equipment on moving platforms such as ships or aircraft where problems could be encountered at any place or time. Even if technical systems are used, social processes may still have to be invoked in order to solve novel problems.

4.2. How to ensure good data quality.

As well as the challenge of getting acceptance of an information system by its users there are also many opportunities for the accidental or deliberate entry of erroneous data in any system. In our studies of information system implementations we have observed accidental misspelling of words in service records and also deliberate use of slang and abbreviations [23]. Modern information systems

can overcome these issues to some extent, but more difficult to address is the deliberate falsification of records, which we have observed being done for example with the intention of replenishing stocks of spares. Fostering and maintaining staff support for the reliable maintenance of information systems is a key priority, as is the participation by staff in knowledge-sharing activities such as forums, newsletters, social networks, mentoring schemes and the like.

4.3. Security and privacy

A great deal of attention has been paid to issues of security in data access, especially in military application contexts [24], and to issues of privacy of personal data and data protection [25] but less attention has been paid to issues of information ownership and intellectual property in situations of dynamic relationships between companies involved in the life cycle of an artefact (for example where one company has built an artefact and another maintains it). Concerns about IPR also limit the possibilities to learn from the aggregation of engineering data – consider for example the benefits that might accrue in understanding costs if we could aggregate cost data from many companies while preserving the ‘anonymity’ of individual pieces of data. In these regards it is suggested that we need developments in three areas:

In standards for the exchange of data sets between organisations working at different points in the supply chain and at different times in the artefact life cycle. Developments in building information modelling (BIM) standards are good exemplars in this respect.

There may be merit in establishing secure ‘confidential intermediaries’ to whom organisations can entrust information for the purposes of sharing or aggregation without divulging it in full to competitors. These intermediaries could be then used by third parties for query purposes or could undertake data mining over large collections of data from multiple sources while maintaining its confidentiality.

4.4. The information funnel and layered information systems.

A final issue to be addressed is the degree of human manipulation and interpretation required in information systems, and the consequent latency in the system. The raw data that can be collected in any project – the emails, conversations, spreadsheets, mathematical and computational models and so on – are aggregated, interpreted and précised in the course of documenting the work. An expert engineer aggregates and interprets many sources of data in the course of making an assessment of the state of an asset. In the context of engineering project we have characterised this as the information funnel, in which information progresses from unrecorded exchanges or ideas, through unmanaged ‘information scraps’ [26] then through personal and local to enterprise collections, as shown in Figure 3. Each stage in this journey involves perhaps an order of magnitude or more reduction in quantities of data but also introduces a delay in access to the data which can take months or years. Similar processes occur in the processing of information in through-life support. This has significant implications for the

design of information systems and for the knowledge sharing and management strategies in an organisation in that it is very difficult to make sense of the mass of data at the ‘left hand end’ of the funnel – a good deal of intelligent processing is needed for sense-making. Furthermore, technical information systems cannot be relied on for knowledge exchanges in the early dynamic stages of projects, and at these times social processes may be much more helpful.

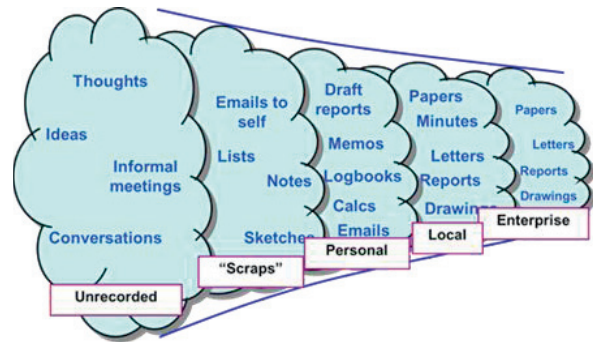


Fig. 3. The ‘Information Funnel’

5. Conclusions

Information systems offer the promise of a number of improvements in the through-life support of long-lived complex artefacts including improved productivity and more accurate and responsive assessment of artefact condition, but in order to realize these advantages a number of challenges, both technical and socio-technical, have to be overcome. Especially, the complexity and interlinked nature of engineering information has to be understood, and it is important to recognize that no matter how technically capable the system it will not function correctly without addressing the security, privacy and other user concerns, and understanding how systems can be embedded in organizational cultures and work practices.

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